# Thermal performance of pulsating heat stripes (PHS) built with plastic materials

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**Abstract**

A low-cost, flexible pulsating heat pipe (PHP) was built in a composite polypropylene sheet consisting of three layers joint together by selective laser welding, to address the demand of heat transfer devices characterized by low weight, small unit thickness, low cost, and high mechanical flexibility. A thin, flexible and lightweight heat pipe is advantageous for various aerospace, aircraft and portable electronic applications where the device weight and its mechanical flexibility are essential. The concept is to sandwich a serpentine channel, cut out in a polypropylene sheet and containing a self-propelled mixture of a working fluid with its vapour, between two transparent sheets of the same material; this results into a thin, flat enclosure with parallel channels hence the name "pulsating heat stripes" (PHS). The transient and steady-state thermal response of the device was characterised for different heat input levels and different configurations, either straight or bent at different angles. The equivalent thermal resistance was estimated by measuring the wall temperatures at both the evaporator and the condenser, showing a multi-fold increase of the equivalent thermal conductance with respect to solid polypropylene.

*Keywords*: Pulsating heat stripes; Plastic heat pipe; Selective laser welding.

## 1. INTRODUCTION

In the recent years, the pulsating heat pipe (PHP) technology has been the object of intensive investigations because of its potential to meet many of the present and future passive thermal management requirements in several applications, including nuclear, defense and aerospace [1-3]. To date, several PHP designs have been proposed and characterised to address electronics cooling [4,5], heat recovery [6,7] and passive cooling of reactor containments, to name a few. However, certain characteristics of state-of-the-art PHPs (their mechanical rigidity, their weight, and their cost) make their use technically and/or economically challenging in several cases. This often prevents potential applications to a range of novel consumer technologies, where mechanical flexibility, weight and cost are critical design and/or marketing constraints.

For example, flexible devices can be applied in multiple potential configurations, where the heat sink is out of plane with the heat source [8]. Early studies, mainly focusing on space applications, proposed to obtain local flexibility in the adiabatic region using bellowed tubes [9,10]. More recently, there was an increasing interest in the development of flexible PHP devices built using thin metal foils, sintered metals [11], polymeric materials [12-14] and micro-machined liquid crystals [15].

However, the approaches proposed so far suffer from several technical issues. Firstly, the fabrication of flexible metallic components is possible only using thin-walled tubes and/or thin metal foils, with severe reduction of their mechanical resistance, in particular to fatigue; this has obvious consequence on the system reliability and operational lifetime. Secondly, these flexible heat pipes are not based on the wickless PHP concept, but the liquid phase circulation is promoted by a micro-manufactured wick structure, such as sintered copper woven mesh [14]; this results into high manufacturing cost and poor mechanical strength. Other technical issues encountered were liquid and gas diffusion through the polymer and billowing of the flexible material due to pressure differentials.

The present work investigates the thermal performance of a flexible, lightweight, low-cost heat pipe technology, which has the potential to overcome the above issues. The basic concept is to sandwich a serpentine channel, which is cut out in a polypropylene sheet and contains a self-propelled gas-vapour mixture, between two transparent polypropylene sheets bonded together by selective laser welding [16]. The resulting channel has a rectangular cross-section characterized by a large aspect ratio, hence the denomination "Pulsating Heat Stripes" (PHS).

The proposed PHS technology has no equivalent among state-of-the-art commercial or research heat transfer devices, both in terms of thermo-mechanical properties and potential applications. In addition, the proposed device can be seen as a novel type of composite polymeric material with enhanced heat transfer characteristics, and significantly higher equivalent thermal conductivity in comparison with the individual component materials.

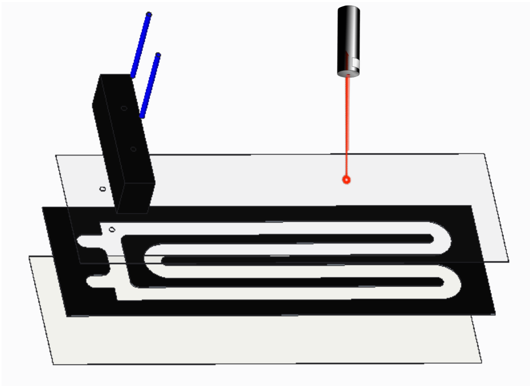

Fig. 1. Schematic of the PHS assembly and laser welding process.

Perspective applications of PHS effective thermal management of passive nature in entirely new devices and materials, such as fabrics equipped with microelectronic devices, whose thermal management is severely hindered at present by mechanical, size, or weight constraints.

## 2. PHS MANUFACTURING

### 2.1 Materials Selection and Fabrication

The manufacturing process, schematically illustrated in Figure 1, consists in cutting out a serpentine channel into a black polymer sheet (0.7 mm thickness), which is placed between two transparent sheets of the same material (0.4 mm thickness each). The three polymer sheets are then bonded together by selective laser welding to create a strong and seamless joint among the three sheets; while the external sheets are transparent to the laser wavelength, the central black layer absorbs the same wavelength, to enable polymer bonding exactly at the interface, without affecting the rest of the material [17,18].

The polymer sheets material (polypropylene) was selected based on: (i) mechanical properties (elastic modulus, yield stress, resistance to fatigue); (ii) compatibility with a range of organic heat transfer fluids (ethanol, acetone, refrigerant fluids); (iii) suitability to laser welding; the maximum continuous service temperature is 130°C. After assembling the three sheets, a PVC block was glued (Loctite All Plastic) in correspondence of two holes in one of the transparent sheets, to fit a pressure transducer and a micro-metering valve used for vacuuming and filling.

The PHS assembly has a length of 250 mm, a width of 98 mm, and a thickness of 1.5, as shown in Figure 2.

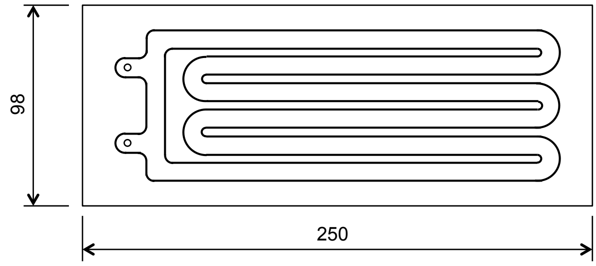


Fig. 2. Schematic of the PHS assembly and laser welding process.

The serpentine has six passes (five turns), and the channel cross-section is 9 mm x 0.7 mm, resulting into a hydraulic diameter $D_H = 1.3$ mm.

$$0.7\sqrt{\frac{\sigma}{g(\rho_L-\rho_G)}} \leq D_H \leq 1.8\sqrt{\frac{\sigma}{g(\rho_L-\rho_G)}} \tag{1}$$

This value satisfies the design criterion given in Eq. (1) to ensure surface forces prevail on gravity [19], using FC-72 ($\rho = 1680$ kg/m$^3$; $\sigma = 10$ mN/m) as working fluid (0.54 mm < 1.3 < 1.4 mm).

### 2.2 Mechanical and Hydraulic Performance

Figure 3 demonstrates the mechanical flexibility achieved with the proposed manufacturing technology; the PHS can be bent at an angle of 180°, with a radius of curvature of approximately 30 mm. However, mechanical flexibility also affects the channel walls, which adjust their shape according to the pressure difference between the working fluid and the atmosphere; in particular, channel walls inflate when $P_{fluid} > P_{atm}$, and appear concave when $P_{fluid} < P_{atm}$.

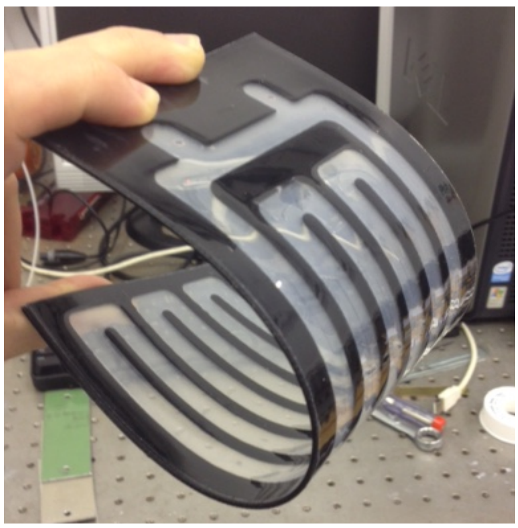

Fig. 3. Demonstration of the PHS flexibility (180° bending).

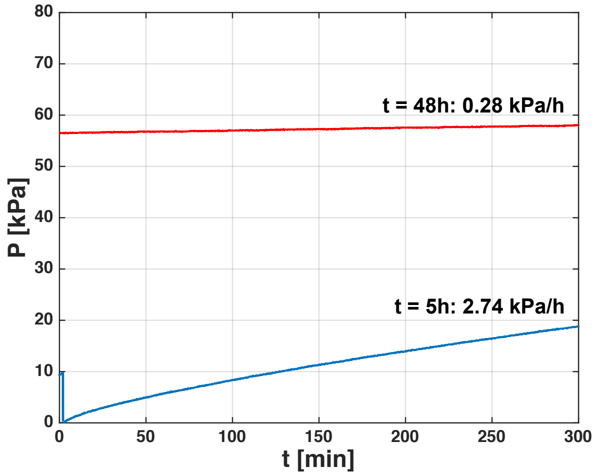


Fig. 4. Schematic of the PHS assembly and laser welding process.

The channel deformation obviously affects the pressure level during the PHS operation, both because of the volume change, and because the pressure difference must balance the stress that builds up in the deformed channel walls, which acts to recover the initial flat shape (Eq. 2); this is similar to the concept of Laplace pressure across a curved fluid interface.

$$P_{atm} = P_{fluid} \pm \tau_{def} \quad (2)$$

An additional complication to account for is that in polymeric materials the deformation stress is not constant, but is subject to stress relaxation, i.e., the observed decrease in stress in response to a certain amount of strain generated in the material. This is usually described using either the Maxwell or the Kelvin-Voigt constitutive equation, or a combination of them [20]. Thus, any pressure change in the PHS channel causes a wall deformation, which in turn induces an apparent pressure change consistent with Eq. (2), i.e. to compensate the stress relaxation in the channel wall.

The peculiar response of the PHS to internal pressure variations may generate ambiguities in the interpretation of pressure measurements. For example, after vacuum is initially created in the PHS, one can still observe an increase in the absolute pressure after closing the micrometering valve, as shown in Figure 4. In a conventional PHP with rigid walls, this would indicate with no doubt a leak, however in PHS with flexible walls the apparent pressure change could be also attributed to the channel wall relaxation.

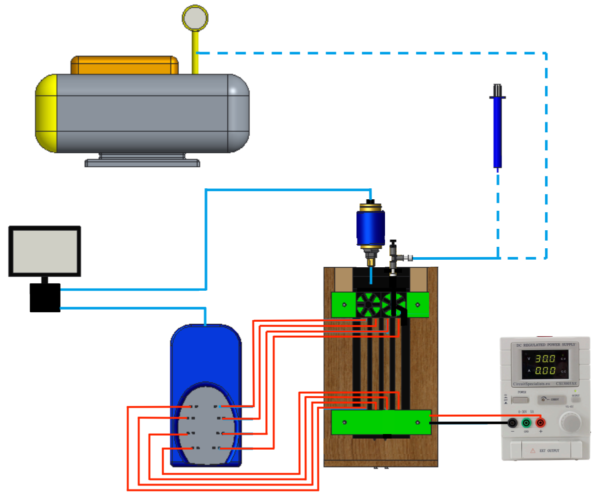

Fig. 5. Schematic of the experimental setup.

Figure 4 shows the measured pressure gradient is 2.74 kPa/h five hours after closing the micrometering valve, and reduces to 0.28 kPa/h after 48 hours, which is sufficiently small to enable testing the thermal performance of the PHS. The exact quantification of the pressure change actually due to the PHS wall relaxation is beyond the scope of the present work.

## 3. EXPERIMENTAL SETUP AND PROCEDURE

### 3.1 Experimental Setup

The experimental setup is schematically shown in Figure 5. The PHS were mounted on a vertical support, with the evaporator zone at the bottom and the condenser at the top. A hinge in the middle of the support plate allowed bending the PHS at different angles between 0° and 90°.

Two ceramic heaters (100 W each) were applied to both sides of the PHS in the evaporator region; heat sink paste was used to minimise the contact resistance and two copper plates were used to distribute the heat supply uniformly. The heaters were connected to a regulated DC power supply (Circuit Specialists CSI 12001X) to enable a fine control of the power input. The condenser was cooled by two fan-assisted heat sinks (Malico).

The heat pipe was connected to a pressure transducer (Gems 3500, 0-160 kPa) and to a micro-metering valve (Upchurch Scientific), used in turn to vacuum the PHS and to fill the PHS with the working fluid. The pressure transducer DC output was sampled at 1 Hz by a data acquisition system (LabJack U6).

Eight surface thermocouples (Omega Engineering) were placed on the heat pipe surface, four in the evaporator zone, and four in the condenser zone, and connected to a data acquisition system. The temperature distribution in the adiabatic region was monitored by a FLIR One infra-red camera (FLIR Systems Inc.).

### 3.2 Procedure

To introduce the working fluid (FC-72), the PHS were vacuumed to a pressure of 0.2±0.5 kPa (abs) using a two-stage vacuum pump (Bacoeng); then, the fluid contained in an external reservoir was slowly driven by the atmospheric pressure into the PHS as the micro-metering valve was gently opened. The amount of working fluid used in the present experiments was 4 mL, i.e. 48% of the total PHS volume (8.4 mL).

Experiments were conducted by applying to the evaporator section an ascending/descending stepped power ramp ranging approximately between 2 W and 30 W, and measuring the temperatures on the PHS surface at a sampling rate of 1 Hz. For each power step, the heat supply was kept constant until a pseudo steady-state regime was attained. Tests were interrupted earlier in case any point of the PHS reached a temperature of 110°C. Preliminary experiments [16] showed the start-up of two-phase circulation in the PHS occurs with a heat input of about 2.5 W at the evaporator.

Experiments were carried out for two PHS configurations: (i) straight vertical arrangement, and (ii) PHS bent at 90° in the adiabatic zone, with vertical evaporator and horizontal condenser.

## 4. RESULTS

### 4.1 Straight Arrangement

Temperatures measured in the evaporator and in the condenser zones of the PHS in straight vertical arrangement during the ascending/descending heat supply ramp are displayed in Figure 6, while the corresponding absolute pressure in the PHS channel is displayed in Figure 7. As expected, both temperatures and pressure exhibit hysteresis, which is partly due to thermal inertia and partly due to the channel wall relaxation discussed in Section 2.2 above.

Figure 8 shows the temperature distribution measured in the adiabatic region for two values of the heat supply at the evaporator (Q = 6.7 W and Q = 21.5 W, respectively). For the lower heat input (Figure 8a), one can visualize ascending plumes of hot boiling fluid and descending colder condensate in the same channel, while for the higher heat input (Figure 8b) individual channels can be clearly distinguished, with their bottom part containing the boiling fluid and the condensate confined in the upper part of each channel.

The overall thermal performance of the PHS is shown in Figure 9, which displays the equivalent thermal resistance of the PHS, calculated as:

$$R = \frac{T_{ev} - T_{cond}}{Q} \quad (3)$$

where $T_{ev}$ and $T_{cond}$ are the averages of the four temperature measurements of the PHS surface at the evaporator and the condenser, respectively,

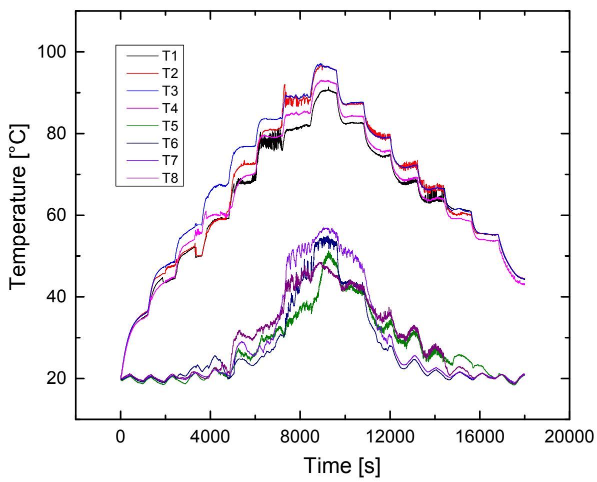


Fig. 6. Temperatures measured in the evaporator (T1-T4) and in the condenser (T5-T8) zones of the PHS in straight vertical arrangement during the ascending /descending power supply ramp.

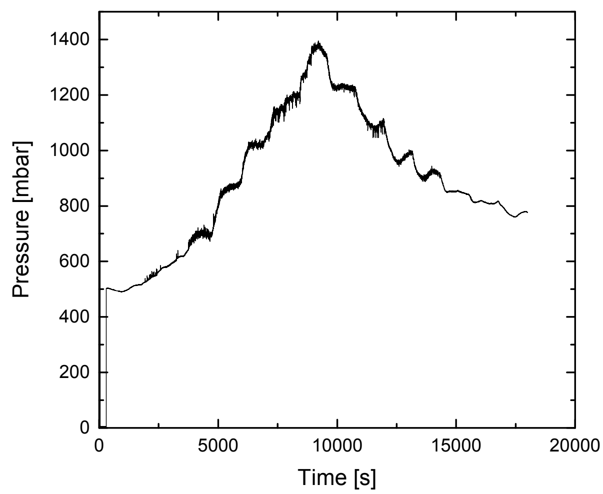


Fig. 7. Absolute pressure measured in the PHS in straight vertical arrangement during the ascending /descending power supply ramp.

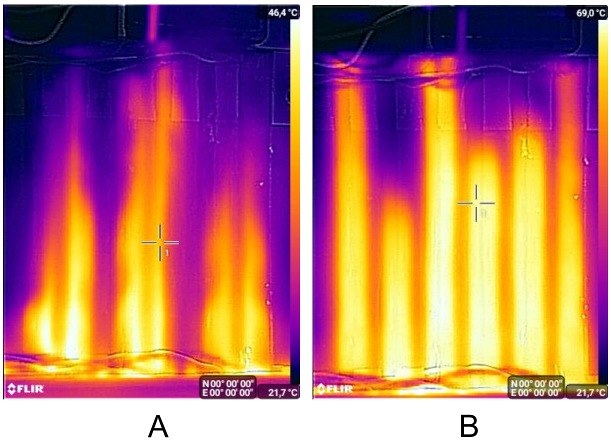


Fig. 8. FLIR images of the adiabatic region during the heating ramp; (a) Q = 6.7 W; (b) Q = 21.5 W.

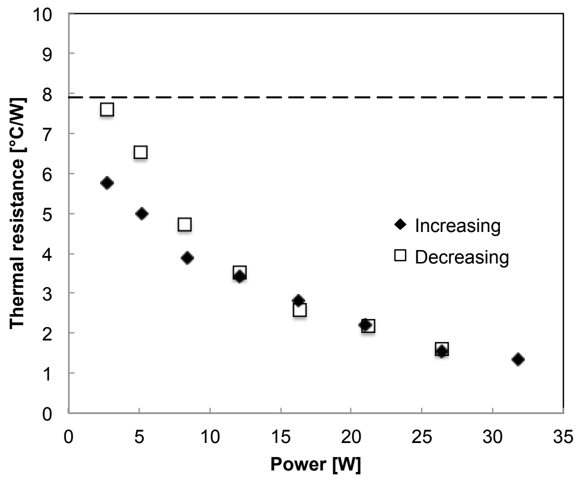


Fig. 9. Equivalent thermal resistance of the PHS in straight vertical arrangement, as a function of the heat rate supplied at the evaporator; the dashed line represents the thermal resistance of the PHS envelope without working fluid.

in the pseudo steady-states corresponding to each level of the power input, $Q$.

At the maximum heat supply of 31.82 W, the equivalent thermal resistance attains a minimum of 1.35 °C/W; in comparison, the equivalent thermal resistance of the PHS envelope without working fluid is 7.9 °C/W, which means the equivalent thermal conductance of the PHS increases of 585% with respect to the composite polypropylene sheet without fluid.

## 4.2 Bent Arrangement

Temperatures measured in the evaporator and in the condenser zones of the bent PHS (angle: 90°) during the ascending/descending heat supply ramp are displayed in Figure 10.

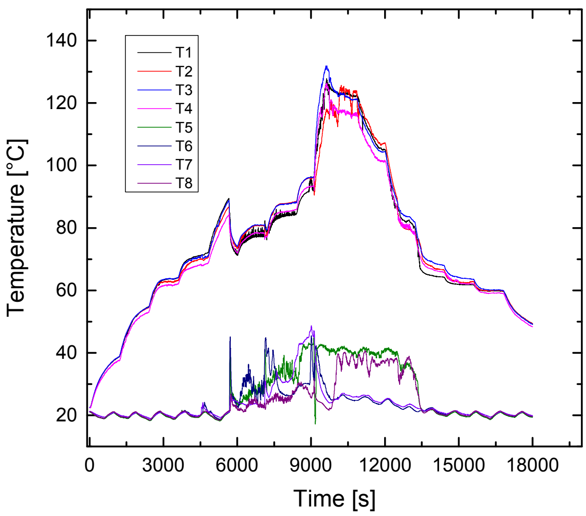


Fig. 10. Temperatures measured in the evaporator (T1-T4) and in the condenser (T5-T8) zones of the PHS bent at 90° during the ascending /descending power supply ramp.

Whilst the evaporator and condenser temperature trends appear qualitatively similar to those observed in the straight vertical PHS, in the bent PHS the evaporator temperature may exhibit a significant overshoot upon increasing the thermal power supply before approaching the pseudo steady-state.

This happens when the vapour generated in the vertical evaporator section remains trapped by buoyancy in the horizontal condenser section, therefore a larger evaporator temperature is necessary to ensure the fluid circulation; at the onset of circulation, the evaporator temperature drops because of rewetting.

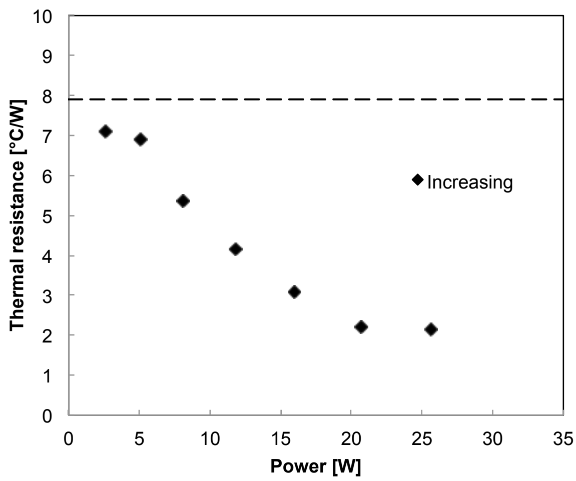


Fig. 11. Equivalent thermal resistance of the PHS bent at 90°, as a function of the heat rate supplied at the evaporator.

The equivalent thermal resistance of the bent PHS is displayed in Figure 11 as a function of the thermal power supplied at the evaporator; at low power inputs ($Q < 0.5Q_{max}$), the performance of the bent PHS is 20% to 40% less than for the straight vertical PHS; at higher power inputs ($Q > 0.5Q_{max}$), the circulation is sufficiently sustained and the equivalent thermal resistances of the two arrangements become comparable.

## 5. CONCLUSIONS

A low-cost, flexible pulsating heat pipe was manufactured using three polypropylene sheets, bonded together by selective laser welding, where the central sheet contains the serpentine channel filled with the working fluid (FC-72).

The thermal response was evaluated for different values of the heat input at the evaporator, and two different geometric configurations: straight vertical, and bent at 90° in the adiabatic zone, with vertical evaporator and horizontal condenser. Initial results indicate a six-fold increase of the equivalent thermal conductance in comparison with that of the composite polymer constituting the heat pipe envelope. This suggests the proposed technology represents a promising route to produce composite polymeric materials with enhanced thermal performances.

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## NOMENCLATURE

$D_H$ : Hydraulic diameter (m)
$g$ : Gravity (m/s$^2$)
$P$ : Pressure (Pa)
$Q$ : Power (W)
$T$ : Temperature (°C)
$\rho$ : Density (kg/m$^3$)
$\sigma$ : Surface tension (N/m)
$\tau$ : Deformation stress (Pa)

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